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"HIGH-VELOCITY IMPACT STUDIES"

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1 INTRODUCTION

This report is a final summary of work done at the University of Utah, High-Velocity Laboratory under Air Force Office of Scientific Research contract AF 49(638)-462 during the period 15 July 1958 to 30 September 1961. During this period, five technical reports have been issued, three technical reports are being submitted with this final report, two papers were presented at the Third Symposium on Hypervelocity Impact and appear in the published proceedings of that symposium, and one paper was presented at the Fourth Symposium on Hypervelocity Impact and appears in the published proceedings of that symposium. These reports and papers are listed in Section 2; their contents will be noted in Sections 3 to 6 where the various research projects conducted under contract AF 49(638)-462 will be discussed. The reports serve as final reports on the various phases of the work and include complete discussions of the objectives, programs, results obtained, and recommendations made for each separate research project. Since these published reports cover all of the work done under this contract, this final report will consist primarily of a compilation of the abstracts of these individaul reports.

This work has provided the material for one Ph.D thesis, seven M.S. theses and one B.S. thesis and has contributed in some degree to six other theses done under other contracts. These theses will not be listed since the work is included in the published reports.

2. PUBLICATIONS UNDER CONTRACT AF 49(638)-462

Reports published by the High-Velocity Laboratory, Department of Electrical Engineering, University of Utah, Salt Lake City, Utah.

Technical Report OSR-16, AFOSR No. TN-60-13, Spectral Analysis of the Impact of Ultra-Velocity Copper Spheres into Copper Targets by J. S. Clark, R. R. Kadesch, and R. W. Grow, September 1, 1959.

Technical Report OSR-17, Analysis and Development of a Light-Gas Gun for Accelerating Pellets to Hypersonic Velocities by K. E. Boyd, R. W. Grow, E. P. Palmer, and E. T. Cannon, October 15, 1959.

Technical Report No. OSR-18, Hypervelocity Impact Spray Particles by W. H. Clark, R. R. Kadesch, and R. W. Grow, May 1, 1960.

Technical Report No. OSR-19, AFOSR No. TN-60-989, Velocity and Size Distribution of Impact Spray Particles by R. E. Blake, R. W. Grow, E. P. Palmer, May 20, 1960.

Technical Report No. OSR-20, AFOSR No. TN-60-719, Preliminary Report on the Investigation of the Feasibility of an Electrostatic Accelerator for Accelerating Micron-Diameter Particles by G. K. Jesperson, D. W. Reid, R. W. Grow, and E. P. Palmer, November 15, 1960.

Technical Report No. OSR-21, Charging, Initial Acceleration, and Detection of Micron-Diameter Particles, by D. R. Harrison, E. P. Palmer, and R. W. Grow.

Technical Report No. OSR-22, A Laboratory Investigation of Meteor Physics, By J. R. Jensen and E. P. Palmer, 15 October 1961.

Technical Report No. OSR-23, Precision Measurement of Lead to Lead Impact, by Ching-hwei Chion, R. W. Grow, and E. P. Palmer, 31 October 1961.

Symposia Papers:

"The Anomalous Behavior of Lead to Lead Impact," by H. B. Van Fleet, W. S. Partridge, and E. T. Cannon in Proceedings of the Third Symposium on Hypervelocity Impact, Armour Research Foundation, Chicago, Illinois, Vol. I, February 1959.

"The Utah Light-Gas Gun," by W. A. Boyd, W.S. Partridge, and E.T. Cannon, in Proceedings of the Third Symposium on Hypervelocity Impact, Armour Research Foundation, Chicago, Illinois, Vol. I, February 1959.

"Experimental Investigation of Spray Particles Producing the Impact Flash," by R. W. Grow, R. R. Kadesch, E. P. Palmer, W. H. Clark, J. S. Clark, and R. E. Blake in Proceedings of the Fourth Symposium on Hypervelocity Impact, Air Proving Ground Center, Eglin Air Force Base, Florida, APGC-TR-60-39, Vol. III, September 1960.

3 IMPACT-FLASH AND SPRAY-PARTICLE INVESTIGATIONS

An investigation was made of the physical mechanisms responsible for the production of the intense flash of light observed in high-velocity impact. A by-product of this research was the discovery of micron-sized particles having velocities up to 20 km/sec. The importance of the discovery that particles with meteor velocities could be produced in the laboratory was recognized and led to the initiation of several projects to study the production and properties of the particles and the means of utilizing them in investigations of meteor impact and meteor flight through an atmosphere. Preliminary work with the particles has shown that they can be reliably produced, their size measured, and flight and impact effects observed. Besides their scientific value, the particles should provide a means for obtaining engineering design information for solving such problems as satellite erosion, micrometeorite-detector calibration and other space-age problems.

This work is reported in OSR-16, 18, 19 and 22 listed in Section 2. Abstracts of these papers follow:

OSR-16, Spectral Analysis of the Impact of Ultra-Velocity Copper Spheres into Copper Targets.

Spectrographic observations were made for copper projectiles impacting into copper targets in various controlled atmospheres. Atomic copper

lines are the predominant feature of the impact flash of copper-to-copper impacts in a medium of argon. Since a copper line with a 7.1 ev excitation energy is excited in an argon atmosphere, an energy of at least this magnitude is available for excitation of copper atoms. Results indicate that in argon, the flash is produced by micron-size copper particles ejected from the target, some with velocities no less than 6-7 km/sec and heated by the medium. A collision process between copper atoms evaporated from the heated spray particles and atoms of the argon atmosphere can account for the observed copper lines.

In a medium of hydrogen, the impact flash is dimmer by at least two orders of magnitude, giving a smooth spectral contour with no detectable line structure. However, no obvious black body temperature is obtainable from the contour of this light emission in hydrogen. The relative velocity between copper atoms and hydrogen molecules required to produce copper lines is greater than 20 km/sec in a collision process.

The reduced size of the flash in hydrogen indicates that the particles responsible for the flash are smaller than those producing the flash in argon. It appears that the size of the particles that produce the flash in each gas is of the order of magnitude of the mean free path of the molecules in that gas.

OSR-18, Hypervelocity-Impact Spray Particles

Several investigators have noticed that a spray of small fast particles is ejected from a fast metal-to-metal impact. The velocity of the fastest spray particles previously observed, measured relative to the more massive body involved in the impact, was twice the impacting velocity.

This study has shown that under certain conditions very much faster spray particles appear when a 3/16-inch diameter carbon-steel sphere, with a velocity of 2 km/sec, impacted on a massive steel target in air at 8 cm mercury pressure, spray particles of about 0.5 micron diameter left the impact at velocities up to 15 km/sec. The velocity was measured by a time-of-flight technique

The effect of varying pellet and target material and the atmosphere on the characteristics of the spray particles was investigated. It was found that all three variables have strong and complicated effects.

A partial theory of the acceleration of spray particles has been developed. Tests made on impacts of special geometry confirmed the theoretical predictions

It is hoped that these fast spray particles will be useful as artificial meteors for research purposes It is demonstrated that the faster spray particles observed are luminous due to the same process whereby the average visual meteor leaves a luminous trail.

<u>OSR-19, Velocity and Size Distribution of Impact Spray Particles</u>

Steel and pyrex spheres having a diameter of 3/16 inch were accelerated with a 220 caliber smooth-bore gun to a velocity of 2.0 kilometers per second. These spheres were impacted on targets of the same material as the sphere. The luminous spray resulting from the impact was detected by means of photocircuits which produced a voltage that was recorded by an oscilloscope camera.

Maximum measured initial spray velocities for the steel-to-steel impacts varied between 8 5 km/sec and 10.3 km/sec and a measured average

velocity between two points for glass-to-glass impacts was in excess of 20 km/sec. The particle radius of the steel spray was calculated from drag data to be between 0.18 and 1.02 microns.

In order to separate the impacting spray particles, a high speed motor was used to rotate a polished aluminum disk at a velocity of thirty-two thousand revolutions per minute. The velocity distribution of the spray particles in the steel-to-steel impacts was observed to have two discrete velocity classes - one at the faster velocity of approximately 9 km/sec and another moving much slower in respect to the initial time of impact. This second discrete velocity class was not observed in the glass to glass impacts. Particles moving at these discrete velocities were of random size. The distribution of the crater size at various angular positions was investigated.

OSR-22. A Laboratory Investigation of Meteor Physics

The equations of motion for a single particle traveling in a constant-density atmosphere are derived. The aerodynamic drag on the particle and the atmosphere-particle energy transfer resulting in loss of particle mass are considered in the derivations. The equations are solved using a Datatron 205 Digital Computer, and the solutions are discussed in some detail. Emphasis is placed on determining particle size and absolute luminosity from measurements of distance versus time. In the solutions, it is assumed as an initial condition that the particles are heated and ablating.

Micron-size particles, which travel at velocities in the lower meteor range of 10 to 20 km/sec, are produced by impact of spherical

steel pellets on a steel target Preliminary experiments were conducted using these particles in a controlled atmosphere The particles, being luminous, were detected by photomultiplier tubes The leading edge of a cloud of particles was detected and velocities up to 15 km/sec were measured By applying the theory to deceleration measurements, the size of the particles was estimated at approximately 1.0 micron diameter.

An improved vacuum firing range was designed to correct for the vacuum and size limitations of the original system. An experiment is proposed to utilize the improved system to detect and measure individual particles. Data from the experiments can be compared with theory and the results applied directly to determine in detail the physical phenomena occurring in meteor flight

4 LIGHT-GAS-GUN DEVELOPMENT

A necessary part of any high-velocity investigation is the development of equipment for accelerating projectiles to the required velocities. To satisfy these needs, a light-gas gun was developed under contract AF 49(638) 462. The work is discussed in detail in report OSR-17 listed in Section 2. The abstract is given below.

OSR-17, Analysis and Development of a Light-Gas Gun for Accelerating Pellets to Hypersonic Velocities

A light-gas gun employing hydrogen as a driving gas and using a piston-type compression cycle has been developed and fired in two different configurations under a variety of firing conditions.

Pellets weighing one gram have been launched through a velocity range of from 7,000 ft/sec to 27,300 ft/sec The high velocity of

27,300 ft/sec has not been verified because of the damage suffered by the gun when fired at the conditions required to achieve this velocity. Rather than risk destroying the gun by attempting to verify the highest velocity achieved, emphasis was placed on gaining data at reduced energy levels to study the launching cycle in a manner to gain maximum knowledge.

Data are presented and analyzed for a gun having a compression tube length of 92 inches with a bore of 2.38-inches diameter and designed to launch pellets either parallel to the longitudinal axis of the gun or perpendicular to the longitudinal axis.

A study and analysis of the piston motion is made and a basis for assuming a shock-wave compression process is determined. Equations describing pressure ratio and temperature ratio across a compression wave and a reflected wave are developed and a comparison of a shock-wave compression process to a reversible-adiabatic compression process is made.

A procedure for firing the gun described in these pages is given in the Appendix with a set of sample firing calculations.

The four basic requisites for successful launching using a piston type light-gas gun are offered as a basis for understanding the actual launching process.

5. ELECTROSTATIC ACCELERATION OF SMALL PARTICLES

A theoretical and experimental study was made of the feasibility of charging small particles and accelerating them to high velocities in an electrostatic field. The development of a Van de Graaff generator for producing the necessary field and the development of methods for handling

the particles are discussed in report OSR-20 listed in Section 2. Final feasibility of the method is determined by the ratio of charge on the particle to the mass of the particle. The results of experimental studies on the charge to mass ratio actually attainable are given in report OSR-21. Abstracts of these papers are given below.

<u>OSR-20, Preliminary Report on the Investigation of the Feasibility of an Electrostatic Accelerator for Accelerating Micron-Diameter Particles.</u>

PART I Van de Graaff Generator

An electrostatic generator of the Van de Graaff type was built. The generator charges to 600,000 volts and delivers 70 μamps when negatively charged. When positively charged, the generator delivers 10 μamps at 475,000 volts. The difference in voltages and currents is due to a difference in arc-over phenomena which is discussed.

It was found that the charge delivered to the upper oblate spheroid is generated by ionization of the air in the vicinity of the lower pulley. The air is ionized by high voltage gradients between comb tips and the lower pulley.

A rubber belt is used to transport charge from the charge-producing system to the upper spheroid. The equation for the electric field due to an infinite sheet of charge is used to predict the theoretical maximum surface charge density on the belt. The maximum charge the belt will carry was found to be about 50% of the theoretical value. It is shown, by the use of electric field maps, that the generator voltage has very little effect on the amount of charge lost in transit from the

lower to the upper spheroid. It is shown that most of the charge is lost before the belt leaves the lower spheroid.

Gauss' law is used to show that the charged belt entering the upper spheroid develops a potential between the belt and the spheroid regardless of the potential of the generator. This potential ionizes the air between the upper comb and pulley which allows the charge to be removed from the belt to the spheroid.

An equivalent circuit is proposed which predicts the voltage attainable by the generator. All parameters in the equivalent circuit are shown to be a function of belt speed only. Agreement is good between predicted and measured performance values at low belt speeds. At the upper belt-speed limit of 4,000 ft/min, errors of 30% are noted.

Recommendations are made for increasing the current and voltage capabilities of the generator.

PART II Charging of Micro Particles

A system was built to handle micron-diameter particles, charge them, and inject them into the field of a Van de Graaff generator. The particles used are carbonyl-iron spheroids having an average diameter of 3 microns and a density of 7.8 g/cm^3. An injector was built which consists of two parallel plates separated by an insulating washer. The application of 2,000 volts dc across the plates causes the particles to oscillate between them. This motion injects the particles into the system when their path lines up with a small hole in the lower plate. The particles are charged when they hit a charging electrode raised to 25,000 volts positive. The charging electrode consists of a ball with a diameter of

50 microns attached to the end of a smaller-diameter shaft. The particles are accelerated by a large dc voltage developed between two large oblate spheroids by a Van de Graaff generator. To measure the charge on the particles and also their velocity, a small section of 1/8 inch copper tubing is enclosed in a grounded shield. The passage of a charged particle through the tubing induces a voltage pulse whose height is proportional to the charge on the particle and whose length is a measure of the time required for the particles to travel the length of the tubing.

OSR-21, Charging, Initial Acceleration, and Detection of Micron-Diameter Particles

One method by which small particles may be accelerated to high-velocities is to charge the particles electrically and then accelerate them through a high voltage such as that produced by a Van de Graaff generator. Besides producing a high voltage, the chief problems met in developing such a system are those concerned with the handling of the particles, the placing of a charge on them, maximizing their charge-to-mass ratio and measuring particle size and velocity. This paper discusses the system developed to solve these problems. A measure of the over-all effectiveness of the charging system is given by the particle charge-to-mass ratio since this determines the velocity which can be attained by electrostatic acceleration. It was found that for carbonyl-iron spheres of 0.2 to 1.1-micron radius, the attainable charge to mass ratio is given by the formula $q/m = (6.13 \times 10^{-6})R^{-1}$ where q is charge, m is mass and R is particle radius. M. K. S. units are used. It is

believed that this represents close to the practical maximum value attainable using induction charging. The results indicate that 0.3-micron-radius particles can be accelerated to about 13.5 km/sec with a 5 MV accelerating potential. It was found that particle mass could be determined within 22 per cent. This serves as a measure of the over-all effectiveness of the detection system since mass is calculated from measured velocity, charge, and accelerating voltage.

6. IMPACT AND CRATERING INVESTIGATIONS

An experimental investigation of cratering in lead was conducted in order to study the behavior of a material where hydrodynamic properties are more important than material strength properties. Earlier work, reported by Van Fleet, Partridge and Cannon in the Third Symposium on Hypervelocity Impact (see Sec. 2), had indicated that crater volume per unit projectile energy decreased at higher velocities. This was in contrast to the experimental results obtained in other materials but tended to substantiate the theoretical predictions of R. L. Bjork.* By carefully controlling experimental conditions in order to obtain more accurate data, it was discovered that for many shots, the ratio of crater volume to projectile energy did not decrease at high velocities. Scatter in the data and a limited velocity range do not allow final conclusions to be made in this matter and indicate the need for further work. The

*R. L. Bjork, Effects of a Meteoroid Impact on Steel and Aluminum in Space, Report P-1662, The Rand Corp., Santa Monica, California, December 16, 1958.

results of this study are reported in OSR-23. An abstract of the paper is given below.

OSR-23, Precision Measurement of Lead to Lead Impact

Lead spheres having a diameter of 3/16 inch (0.476 cm) were impacted normally upon lead targets at different temperatures. The volume, area. and depth of resulting craters were measured and plotted as a function of either the pellet impacting energy, the pellet momentum, or the pellet velocity.

The crater volume was found to be a linear function of the pellet impacting energy for low energies. The ratio of volume to energy was found to decrease with the increase of pellet velocity. The decrease of this ratio at higher velocities was found to be less with the increase of target temperature. The temperature dependence of volume per unit energy was contrary to that expected since it was believed that at higher temperatures, material strength would be less and the material would behave more like a perfect fluid. It was expected that a more fluid behavior would result in a lower volume per unit energy as predicted by R. L. Bjork for iron and aluminum.

In order to increase the accuracy of measurement, shadowgrams of pellets were taken just before the impact. These were used to decide the accuracy of data obtained. In these more accurate experiments, the crater depth was found to be proportional to the two-third power of pellet velocity for many shots over the entire velocity range investigated. Since the craters were practically hemispherical, this indicates volume proportional to energy for these shots. The original

results that V/E decreases with the increase of pellet velocity and the later results that crater depth is proportional to the 2/3 power of pellet velocity contradict each other But the fact that the decrease of V/E at high velocities is less at high temperature and thus the volume versus energy plot tends to be a straight line shows that the contradiction is probably caused by measurement error. The error is greater for high velocities and low target temperatures. The results of this work are not conclusive and indicate the need for the development of better means of accelerating low-strength projectiles.

A relationship was found to exist between the initial V/E and the target temperature. A linear relationship between the crater area and the pellet momentum was found to exist.